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Accelerating hydrogen implementation by mass production of a hydrogen bus chassis

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Abstract

Much of the hydrogen vehicle research to date has been conducted and demonstrated in wealthy nations, with very few exceptions. However, developing economies are largely dependent on public transportation, and struggle with air pollution and energy security concerns. The developing regions are in great need of alternative transportation solutions, and although many alternatives are being explored, hydrogen-fueled vehicles are emerging as one of the only technologies that can meet the demands for lower greenhouse gas emissions, lower emissions of air pollutants, and reduced dependence on imported energy. Many conventional buses in developing regions are built from an imported 'buggy-chassis', which is a functional bus chassis with an engine and other auxiliaries. 'Buggy-chassis' are designed with a very short wheel-base dimension to reduce freight costs as they are often shipped overseas. Domestic companies extend the 'buggy-chassis' to full bus length, build the body and cabin, and install other auxiliary systems. The existing infrastructure of the bus buggy-chassis market can be used to leverage hydrogen technology for mass production. This solution allows developing nations to import a state-of-the-art vehicle, with the possibility for local content in the final delivered product, while maintaining the flexibility for innovative technological developments and promoting hydrogen research within the developing economies. Indeed, a modular series-hybrid drivetrain can be made adaptable to a range of primary power sources such as an internal combustion engine or fuel cell engine. The modular approach provides an opportunity to reduce cost while still providing flexibility for innovation, and allows customers to tailor performance to suit their topographical and operational needs.

Keywords: Transportation; Hydrogen; Fuel cell; Hydrogen combustion; Alternative energy

Contents

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1. Introduction

The interest in hydrogen bus projects has increased substantially over recent years, with significant investment from both the public and private sectors. A market survey by Fuel Cell Today reported a reduction in the number of new buses on the road in 2006, but anticipated increases in 2007 and 2008 due to several new initiatives announced during 2006 [1]. Several alternative fuel pathways are being explored through demonstration and pilot-scale projects around the world, with hydrogen fueled transportation emerging as one of the only alternatives that can address the three core concerns of reduced greenhouse gas emissions, reduced emissions that contribute to air toxicity in cities, and independence from imported crude oil.

1.1. The growing global transport task

Population and economic growth have increased the transport task in many cities around the globe. In the United States alone, the public transportation ridership has been growing at more than double the US population increase since 1995 [2]. While many of the wealthier nations of the world continue to grow at a steady pace, the growth in some developing nations has been staggering. Historical trends have shown that economic expansion has always been coupled with increasing transport energy demand, and more than 62% of the increase in global primary energy demand between 2000 and 2030 is expected to occur in developing nations [3]. It is these developing economies that can best benefit from the broad implementation of efficient and innovative modes of mass transportation before a broad dependence on energy-intensive private automobiles takes hold. The majority of the population in developing nations is already quite efficient, with a heavy reliance on public transportation or non-motorised transport such as walking and cycling, as shown in Fig. 1. However, if current trends continue the number of cars worldwide is expected to double by 2030, with the most significant growth in the developing regions [4]. Many of these regions already exhibit a very high use of energy for private transportation relative to their Gross Domestic Product (GDP), with low-income Asian and Chinese cities surpassing Western European cities in car passenger kilometres per $1000 GDP, as illustrated in Fig. 2 [5]. This apparent contradiction can be attributed to the wealthy minority using personal vehicles while the majority of the population commutes by more efficient means. If business continues 'as usual' the International Energy Agency (IEA) predicts China and India will need to import 90% of their oil requirements in 2030 [3], and the United States Energy Information Administration anticipates world oil supply will peak in 2030 [6]. If developing nations evolve the same fossil-fuel based automobile dependence that has been established in OECD nations then the long-term prospects for future environmental and energy security concerns are dire.

1.2. The importance of energy efficiency in transport

One way to reduce the energy required for transport is to optimise efficiency, thereby reducing the fuel consumed per passenger-kilometre and reducing all emissions proportionally. The Life Cycle Assessment (LCA) of bus transportation has shown that fuel economy is a key parameter governing the emissions profile and primary energy demand over the entire lifecycle of the vehicle [7]. Fig. 3 shows the relative efficiency for various modes of transportation, based on data collected

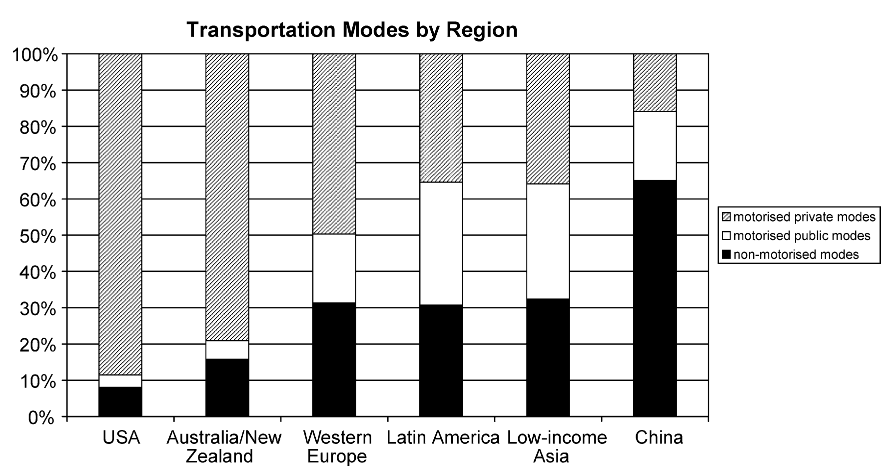

Fig. 1. Comparison of transportation modes in various regions, generated from data published in [5].

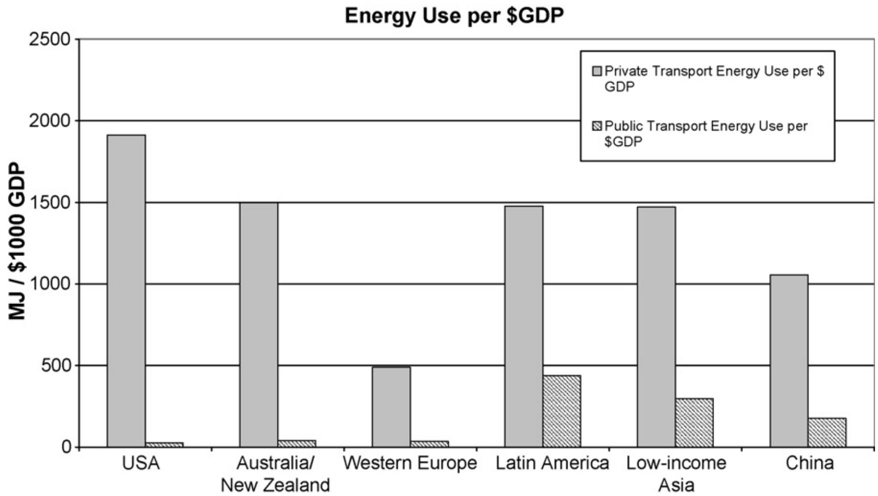

Fig. 2. Comparison of transport energy use per $GDP for selected wealthy and developing regions, generated from data published in [5].

from the Public Transport Authority in Perth, Australia [8], the Sustainable Transport Energy Programme (STEP) fuel cell (FC) EcoBus trial [9], and industry expectations for a next-generation FC vehicle [10–14]. Rail is the most efficient mode of transportation, and a system using electrified rails creates no tailpipe emissions [15]. If a rail system could be supported by renewable power generation then the rails would effectively be a zero emission solution. However, the construction of new rail lines requires time and land, cutting rail corridors through the most popular parts of a city and displacing residents and businesses at significant cost.

1.3. The role of hydrogen

An effective transportation network is a necessity in any modern, vibrant society, and can be shaped through careful strategic planning. Singapore is an example of a nation that has successfully limited the number of automobiles while simultaneously improving public access to efficient transportation, by providing a reliable network of buses, taxis, and Mass Rapid Transit (MRT) rail [16].

The global transportation sector is faced with the dual objectives of reducing transport energy consumption per capita in the industrialized regions without reducing living standards, while implementing innovative technology in developing regions that will allow living standards to increase without a dependence on oil-fueled transport [17]. The early transition to a domestic source of transport fuel can avert future geo-political struggles over depleting fossil resources. The IEA has reported that substantial implementation of alternative transport fuels may be required by 2030, and that hydrogen is one of the only alternatives that can enhance energy security while still providing significant CO_2 reductions [18].

1.4. The application of hydrogen buses to the global passenger transport challenge

With personal vehicles becoming an expensive and inefficient option, and long lead times required to build new rail networks, buses emerge as the only mode of transportation that meets the immediate need for improved transport efficiency. Further, when accounting for health effects and damages due to air pollution, a zero-emission hydrogen bus achieves significant reductions in societal lifecycle costs [19], as well as a reduction in lifecycle greenhouse gas emissions [20]. The United Nations Environment Programme (UNEP)

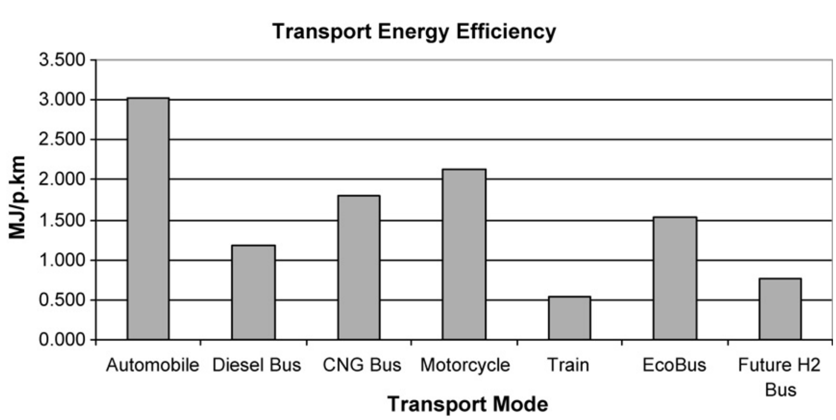

Fig. 3. Energy efficiency of different modes of passenger transportation in Perth, Australia, and comparison with current and future hydrogen fuel cell bus technology.

Global Environment Facility (GEF) administers a project intended to fund demonstration FC bus projects in Sao Paolo, Mexico City, Beijing, Shanghai, Cairo, and New Delhi [21]. These are some of the largest public transportation markets in the world where buses provide a large share of the public transport task. The GEF provides a good framework for international collaboration on such an important project, however the processing time to put buses on the road has been quite extensive in comparison to similar trials in North America and Europe. The Brazilian and Chinese GEF programs are underway, while the Egyptian, Mexican and Indian programs have been cancelled. All three cancelled programs cited a combination of unanticipated technological, economic, and bureaucratic issues, complicating the implementation of fuel cell bus technology [22]. During the same general time period very successful trials of hydrogen buses have been completed in Europe, North America, and Australia [23–27]. A unique opportunity now exists to take the learning from successful demonstrations of hydrogen buses in wealthy nations and leverage that knowledge to push through some of the challenges preventing hydrogen bus implementation in developing regions [28]. Such a strategy can have a positive-feedback effect on the growth of hydrogen bus fleets around the globe by increasing production volumes, thus capturing the benefits of economies of scale, which in turn provokes further research and cost reduction. Innovation and cost reduction allows further expansion of hydrogen bus fleets in wealthy nations and developing countries alike. For the next few years, hydrogen bus projects will likely be relatively small in numbers, and scattered around the globe. The benefits of mass production can be accelerated by the establishment of a global standard for hydrogen bus manufacturing and a modular design allowing the flexibility to incorporate new innovations within the framework of the standardised bus chassis.

1.5. Hydrogen bus design and the opportunity for market expansion

The market for hydrogen buses is relatively small, which requires bus manufacturers to control prototyping costs by minimising the extent of modifications to the bus chassis and body. The design approach for hydrogen buses has been to integrate hydrogen- and hybrid-specific components within the architecture of a conventional complete bus. On the Gillig fuel cell bus operated by the Santa Clara Valley Transport Authority [29] the fuel cell modules are located in the cavity that would normally be occupied by the diesel fuel tank, while on the Mercedes Benz Fuel Cell Citaro operated by the HyFLEET:-CUTE program [24] the fuel cell modules and other auxiliary systems are placed on the roof increasing the overall height dimension of the vehicle. On the Van Hool fuel cell buses operated by AC Transit [30] the fuel cell module is located in the rear engine bay where the diesel engine would normally be placed. Systems integration company ISE Corporation [31] has developed several hybrid buses by integrating the drivetrain, hydrogen storage systems, and hybrid modules within a wide range of existing vehicle platforms.

In all cases the vehicle is delivered complete to the customer with the hydrogen engine fully integrated. As will be explained in the sections that follow, this arrangement differs from the contractual framework of bus procurements in a large segment of the international diesel bus market—many nations import the chassis and engine, and contract local companies to add value to the bus by building the body and auxiliaries upon the imported components. By delivering complete hydrogen buses, suppliers have effectively precluded these nations from adding value in the hydrogen bus supply chain. Hydrogen bus components have now reached a level of maturity which would allow conformance to the existing bus procurement procedures in this market segment, thus encouraging the uptake of hydrogen buses in these regions and substantially increasing the global effort to commercialise hydrogen technologies.

2. The bus chassis market

In the cities of developing nations, mass transport is the only available means for the majority of the population (besides non-motorized modes), with the main transportation mode being public and private buses [32].

Many of the buses currently used in developing economies, as well as in wealthy nations such as Australia, share a common method of bus construction—a *buggy-chassis* is imported, complete with engine, suspension, steering, brakes, and other bus system auxiliaries. The buggy-chassis is essentially a fully functional driving bus chassis. Local companies cut the chassis and extend it to full bus length, build up the body and interior upon the extended chassis, and install body and roof-mounted systems such as heating, ventilation and air conditioning systems, or compressed natural gas (CNG) cylinders [8,33].

The buggy-chassis' are manufactured in different locations around the world, and conform to standard dimensions and interfaces. Body manufacturers can easily adapt their designs to suit a buggy-chassis from any of the major manufacturers. A large fraction of the global market for new buses is based on the buggy-chassis manufacturing concept, as this strategy provides access to modern drivetrain design from European and North American companies, with local industry adding value to the final product in the form of bus bodies and other auxiliaries.

The market for buggy-chassis' is strong, and is steadily growing. DaimlerChrysler, one of the world's largest manufacturers of buggy-chassis' and complete buses, sold the same number of buses in 2006 as were recorded in 2005. However, they reported an increase in chassis sales to 24,300 units in 2006, from 24,000 units in 2005, and declining sales of complete buses, from 12,200 in 2005 to 11,900 in 2006 [34].

3. Current status of hydrogen bus technology

One of the largest, most public, and most successful demonstrations of FC bus technology was the Clean Urban Transport for Europe (CUTE) and its partner projects, the Ecological City Transport System (ECTOS) in Iceland, and STEP in Australia. These programs put 33 buses on the road in 11 different cities for 2 years. Many of the buses have continued

operation beyond the 2-year mark under extension through the HyFLEET:CUTE program, which also trials Hydrogen Internal Combustion Engines (H_2ICE) in addition to the FC buses that were originally procured as part of the CUTE, ECTOS and STEP trials [24]. In the United States, recent hydrogen bus trials in California have also put the technologies to work in regular public service with results reported by the National Renewable Energy Laboratory (NREL) [26,27].

Future generations of hydrogen buses will use hybrid architecture to improve energy efficiency and capture the benefits of regenerative braking. A hybrid powertrain also improves the lifetime of the primary power source on board the vehicle by allowing a FC or H_2ICE to spend more time running in the best efficiency regions of the operating range. The power variation of the primary power source is one of the most important parameters in evaluating different hybrid concepts [35], with a parallel-hybrid placing more of the load directly on the primary source while a series-hybrid buffers the primary source from transient power demands. The schematics in Fig. 4 illustrate some simplified conventional and hybrid powertrain configurations. Shifting the operating profile away from the drastic power variations required to meet a typical automotive drive cycle, and towards a steady-state profile, is highly desirable. A conventional automotive drivetrain experiences frequent transients, with pressure and power fluctuations due to the rapidly changing load. The dynamics of transient operation have a detrimental effect on the lifetime of any machinery, particularly fuel cells, due to the more vigorous load cycling. In the case of a series-hybrid drivetrain the battery pack, or ultracapacitors, absorb the transient demands of the drive cycle,

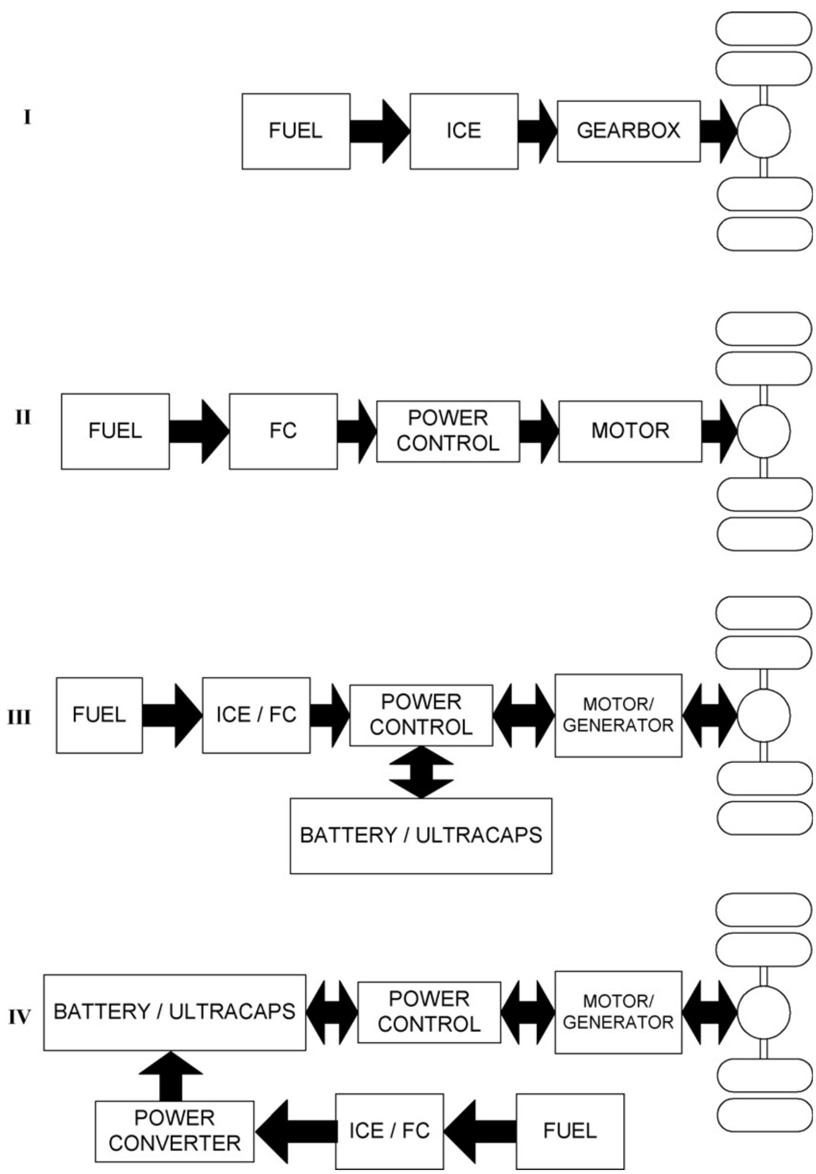

Fig. 4. Simplified schematic of powertrain configurations: (I) conventional direct-drive powertrain powered by a diesel, CNG or H_2 internal combustion engine (ICE); (II) direct-drive fuel cell (FC) powertrain with an electric motor driving the wheels; (III) parallel-hybrid configuration powered by electricity from either an FC or an ICE that is coupled with a generator. A battery pack or ultracapacitor bank provides energy storage and assists the primary power source; (IV) series-hybrid configuration powered by electricity from either an FC or an ICE that is coupled with a generator. The primary power source charges a battery pack or ultracapacitor bank, which in turn powers the motor.

while the expensive FC or H_2ICE power source runs mainly at steady state.

3.1. FC vs. H_2ICE

The decision to invest in FC or H_2ICE as the primary power source on board a bus is subject to ongoing debate and will be heavily influenced by future technological developments. There are a few fundamental facts that can be used now to guide future research.

The emissions from an H_2ICE are only water and oxides of nitrogen (NO_x); a vast improvement over conventional diesel and CNG technologies. A reduction to very low NO_x can be achieved by ultra-lean operation, resulting in a tradeoff between NO_x emissions and power output. Another option is exhaust gas after-treatment such as exhaust gas recirculation (EGR) or use of a three-way catalyst (TWC) [36].

The thermal efficiency of an H_2ICE is approximately 25%, while a FC of equivalent power achieves 50% efficiency [4]. As discussed in Section 1, the efficiency of the vehicle is of paramount importance as fuel consumption dominates the lifecycle emissions profile [37].

According to bus operators, CNG buses are not as powerful and do not perform as well as a diesel bus of equivalent power rating [38]. This loss in power density will be exacerbated for an H_2ICE due to the low volumetric energy density of hydrogen and the corresponding displacement of air in the intake mixture. For purposes of comparison, a stoichiometric mixture of hydrogen and air consists of 30% hydrogen by volume, while a stoichiometric mixture of fully vaporised gasoline and air consists of approximately 2% gasoline by volume [36].

One of the key arguments supporting H_2ICE over FC technology is the economical advantage. The use of conventional engine technologies reduces the development cost and design iterations required to produce an H_2ICE powerplant. In essence, internal combustion engines are a well-understood technology and do not require any special materials, whereas FC stacks and support systems are very much in their infancy and require special materials such as platinum group metals. In addition, FC engines require hydrogen with a minimum purity of 99.999%, which can be expensive to produce. H_2ICE powerplants can be fuelled with hydrogen of reduced purity therefore stripping cost out of the fuel production process. However, many hydrogen stations will only dispense hydrogen of very high purity to maintain full conformance with the fuel cell vehicle specifications. The National Renewable Energy Laboratory (NREL) recently reported on a trial of FC and H_2ICE buses at SunLine Transit Agency in California, and found that the energy efficiency of the FC bus was 71% higher than that of the H_2ICE bus [26]. The bus purchase costs at SunLine were \$3.1 million USD for the FC bus, and \$1–2 million USD for the H_2ICE bus, while a conventional CNG bus costs \$375,000 USD. The cost to acquire H_2ICE technology is significantly lower than FC technology, yet still much higher than conventional technology. When taking the purchase cost of the vehicle and the cost of hydrogen fuel into account, neither FC nor H_2ICE will be cost-competitive with conventional diesel or CNG technologies in the near-term, thus it may be premature to base investment decisions between FC and H_2ICE solely on the economic merits.

3.2. Technical improvements in FC buses

The current FC buses on the road in Perth as part of the STEP trial have achieved an energy efficiency slightly worse than the diesels, and better than the CNG buses [9]. These buses are designed to demonstrate reliability rather than efficiency, and as such a number of design tradeoffs have been made to improve reliability and reduce cost at the expense of energy efficiency. For example, the STEP FC bus is not a hybrid, uses a standard ZF transmission, and consumes hydrogen when the bus is idle to keep the bus auxiliary systems running and to keep a minimum load on the fuel cells [39]. The CUTE Detailed Summary of Achievements discusses the potential for future optimisation of the electric drivetrain and fuel cell system [23]. As noted in Section 1.2, it is widely accepted that the technology now exists to build reliable FC vehicles with energy efficiency more than two times greater than conventional vehicles. SunLine in California have already demonstrated an FC bus energy efficiency 2.5 times higher than their CNG bus fleet [26].

4. Barriers against mass production of hydrogen buses

Previous hydrogen demonstration projects have overcome a number of significant barriers, and their contribution to a future hydrogen economy cannot be overstated. However, many challenges remain in the technical, economic, and public perception domains, in addition to the necessity of an adequate hydrogen fuel infrastructure. The bus industry is an excellent platform to push through many of the barriers currently preventing large-scale introduction of hydrogen as a transport fuel. Buses are relatively flexible in construction and can accommodate diverse powertrain components, they have central refueling and maintenance facilities, are operated by limited numbers of drivers, have high daily utilisation, and attract high public visibility.

4.1. Economic barriers

The main barrier preventing mass production is cost, which will remain an uncertainty until an initiative is taken to break into large volume production. The cost of a FC bus is currently estimated to be between \$2 and \$3 million US dollars [26]. The US Department of Energy (DOE) provides regular reports on the state of the technology and the progress against cost and performance targets [40].

The high cost of FC drivetrains can be attributed to a number of components, but particularly the FC stack itself. Ballard Power Systems, the world leading fuel cell manufacturer, has reported that they are on track to meet the DOE 'cost per kilowatt' fuel cell target for 2010, which is based on a production volume of 500,000 units per year [41]. The International Organization of Motor Vehicle Manufacturers

(OICA) reported 337,573 buses and coaches produced globally in 2005. The entire global bus market is not large enough to achieve the DOE definition of *mass production*, however the DOE targets are based on sales of 80 kW automotive fuel cells mainly for car applications. As a point of reference, the buses of the STEP project use 300 kW fuel cells. One possible scenario is for FC buses to lead FC cars in production volume for several years into the future, thus bringing incremental reduction in cost from *economies of scale*, along with new innovations in design and an expansion of the crucially important hydrogen infrastructure.

A necessary step towards mass production is an upfront investment in nonrecurring costs to develop a system suitable for larger volumes. Hydrogen cars have not yet been able to make this transition, however the demand for hydrogen buses has increased significantly, as noted in Section 1. A hydrogen bus buggy-chassis is one uniform product that can meet the demand for small hydrogen bus fleets in many cities around the world.

4.2. Reduction in curb weight

Hydrogen buses have historically been much heavier than their diesel and CNG counterparts. The curb weight of the STEP EcoBuses is 30% greater than the conventional diesel buses on the road in Perth, and 21% greater than the CNG buses [37]. The FC and H_2ICE buses demonstrated at SunLine Transit Agency weighed 21% and 8% more than a conventional CNG bus, respectively [26]. There are many opportunities for weight reduction through optimisation of materials and component design, as well as improvements in overall engine layout. The overall weight of any vehicle must be minimised to achieve optimum fuel economy, and the curb weight of a heavy-duty vehicle such as a bus has implications on the maximum load that can be safely carried due to maximum axle ratings.

Weight reduction is another area where designs should be optimised before beginning mass production, however progress toward optimisation will be very limited until a large-volume market is identified to underwrite the engineering costs. Again, an initial investment in nonrecurring costs must be undertaken before the benefits of large volume production can begin to unfold.

4.3. Dissemination of knowledge and understanding

Hydrogen bus projects cannot be successfully implemented without public support for the use of hydrogen as a transport fuel, and a sense of safety regarding hydrogen vehicles. Bus companies, drivers, and maintenance personnel, must also be comfortable and supportive of new initiatives in hydrogen-based transport. Previous and currently running hydrogen bus programs have made significant headway in public perception and education of industry professionals, and have established hydrogen fueling infrastructures in many cities. Surveys conducted during the STEP trial in Perth recorded a significant increase in support for large-scale hydrogen bus implementation after the hydrogen buses had arrived, and positive associations with the word 'hydrogen' [42]. Locations that have not hosted hydrogen vehicles before will require similar efforts to educate and measure public comfort levels with the use of hydrogen, to accumulate local expertise in hydrogen vehicle operation and hydrogen handling, and to educate the general public and key decision-makers in the benefits of hydrogen as a transport fuel.

5. Leveraging the infrastructure of the chassis export market

The bus buggy-chassis industry is well suited to provide a method of overcoming the barriers preventing mass production of hydrogen buses. A truly global market that sells to the developing nations, with established channels for product imports and dissemination of knowledge and training, provide the necessary infrastructure to rapidly rollout mass-produced hydrogen buses.

5.1. Chassis layout

A series-hybrid drivetrain can be adapted to a bus buggy-chassis without making significant modifications to the existing structural design. Electrical and pneumatic interfaces to systems installed by the body manufacturer can be left as standard, with a new module dedicated to the auxiliaries such as air compression, power steering, heating, and air conditioning. A functioning hybrid bus chassis can be supplied to the buggy-chassis market, with the modularity to run an H_2ICE or FC as the primary power source. Components such as the electric motors, battery packs, ultracapacitors, FC modules, or H_2ICE powerplants, can be installed in the buggy-chassis along with auxiliary systems, resulting in a fully functional driving chassis, similar to today's conventional diesel and CNG buggy-chassis'. The body manufacturer can install hydrogen storage cylinders, and possibly additional radiators, on the roof. The pre-determined chassis dimensions and standard body interfaces provide the constraints for the sizing of a modular system.

Based on the topography of an individual city, the electrical power storage and primary power source can be sized to suit the terrain. A city with mountainous terrain may require a large primary power source with a small battery module to maintain high power during hill-climbing and high average speed operation. Alternatively, a city with low average speed and frequent start/stop operation, and long periods of idle, could achieve better energy efficiency with a small primary power source and a large battery or ultra-capacitor bank.

5.2. Aluminium body manufacturing

An added benefit of the chassis-export market is that the bodies are often manufactured from aluminium extrusions. An aluminium body effects a reduction in the overall vehicle mass in comparison to a steel frame, with associated benefits in energy efficiency. The flexibility of the bolted aluminium construction is an additional advantage, as it can be modified to accommodate design changes due to technological innovations. In comparison, a steel space-frame constrains the drivetrain

design to pre-determined cavities for the engine and other equipment. The lower yield strength of aluminium in comparison to steel will not be a limiting factor in mounting hydrogen storage systems on the roof. Hydrogen bus designers can reference the precedent set by the CNG bus industry, where the bolted aluminium body has sufficient strength to bear the load of roof-mounted CNG fuel storage cylinders [43].

5.3. Expanding the world of hydrogen research

Many cities around the world have proven that operators and maintainers can be trained to work with alternative fuels such as natural gas and propane in a short timeframe, and hydrogen should be no different in its implementation. The uptake of hydrogen technology can be accelerated through widespread training and dissemination of information to engineers and mechanics in transition economies. Such a move would reduce the concentration of intellectual property in the wealthy nations and mobilize the efforts of capable scientists and engineers in the developing regions, spreading the overall knowledge and helping to resolve technological barriers with innovative new solutions. Indeed, the accumulation of knowledge and understanding in regions that have not been exposed to hydrogen technology can have a positive feedback effect that resonates throughout a society. Hydrogen infrastructures will be established, renewable energy sources will be explored, and the general population will become more aware of the importance of energy efficiency. The large-scale implementation of FC buses comes at a high price and may only have a marginal effect on a society's energy and emissions profile, but as has been noted in the field of Consequential Life Cycle Assessment, it must be realised that marginal changes to a subsystem can contribute to radical system change [44].

6. Conclusions and future research

The design of a hydrogen-fueled buggy-chassis brings the industry much closer to the critical cost reductions required for large-scale implementation of efficient, zero-emission transport, with the particular anticipation of providing hydrogen buses to developing cities that rely heavily on bus transportation.

In the broader sense, a hydrogen bus network can lead to wider implementation of hydrogen technology, the dissemination of knowledge and expertise around the world, and a better opportunity for global research and development into innovative new solutions.

A modular approach to the buggy-chassis with a series-hybrid drivetrain provides the flexibility to explore many power sources, energy storage options, and control algorithms, while reducing cost through mass production of the common components required to power the auxiliaries on board every bus. This requires the exploration of many technology options that are currently being researched around the world, including:

- A modular series-hybrid architecture;
- Sizing of modular primary power sources and energy storage modules to suit topography and operation profile;
- Interchangeable fuel cell or ICE, with supporting auxiliary packages;
- Interchangeable battery bank, ultra-capacitors, or other energy storage medium;
- Standard interfaces between the modules;
- Standard electric drive motor and regenerative braking capabilities;
- Standard engine controller minimizing the cost of software development while providing the flexibility to attempt new control algorithms;
- Standard auxiliaries package, with flexibility to size the system for global climates, i.e. powerful air conditioning capability in hot climates or powerful heating capability in cold climates;
- Standard suite of training modules and workshop requirements.

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